Grain Dynamics In Magnetized Interstellar Gas

A. Lazarian & Huirong Yan

Department of Astronomy, University of Wisconsin, 475 N. Charter St., Madison, WI53706; lazarian, yan@astro.wisc.edu

ABSTRACT

The interstellar medium is turbulent and this induces relative motions of dust grains. We calculate relative velocities of charged grains in a partially ionized magnetized gas. We account for anisotropy of magnetohydrodynamic (MHD) turbulence, grain coupling with magnetic field, and the turbulence cutoff arising from the ambipolar drag. We obtain grain velocities for turbulence with parameters consistent with those in HI and dark clouds. These velocities are smaller than those in earlier papers, where MHD effects were disregarded. Finally, we consider grain velocities arising from photoelectric emission, radiation pressure and H_2 thrust. These are still lower than relative velocities induced by turbulence. We conclude that turbulence should prevent these mechanisms from segregating grains by size.

Subject headings: ISM:dust, extinction—kinematics,dynamics—magnetic fields

1. Introduction

Dust is an important constituent of the interstellar medium (ISM). It interferes with observations in the optical range, but provides an insight to star-formation activity through far-infrared radiation. It also enables molecular hydrogen formation and traces the magnetic field via emission and extinction polarization. The basic properties of dust (optical, alignment etc.) strongly depend on its size distribution. The latter evolves as the result of grain collisions, whose frequency and consequences depend on grain relative velocities.

Various processes can affect the velocities of dust grains. Radiation, ambipolar diffusion, and gravitational sedimentation all can bring about a dispersion in grain velocities. It was speculated in de Oliveira-Costa et al. (2000) that starlight radiation can produce the segregation of different sized grains that is necessary to explain a poor correlation of the microwave and $100\mu m$ signals of the foreground emission (Mukherjee et al. 2001). If true

it has big implications for the CMB foreground studies. However, the efficiency of this segregation depends on grain random velocities, which we study in this paper.

Interstellar gas is turbulent (see Arons & Max 1975). Turbulence was invoked by a number of authors (see Kusaka et al. 1970, Volk et al. 1980, Draine 1985, Ossenkopf 1993, Weidenschilling & Ruzmaikina 1994) to provide substantial relative motions of dust particles. However, they discussed hydrodynamic turbulence. It is clear that this picture cannot be applicable to the magnetized ISM as the magnetic fields substantially affect fluid dynamics. Moreover dust grains are charged, and their interactions with magnetized turbulence is very different from the hydrodynamic case. This unsatisfactory situation motivates us to revisit the problem and calculate the grain relative motions in magnetized ISM. In what follows, we use the model of MHD turbulence by Goldreich and Sridhar (1995, henceforth GS95), which is supported by recent numerical simulations (Cho & Vishniac 2000, Maron & Goldreich 2001, Cho, Lazarian & Vishniac 2002a, henceforth CLV02). We apply our results to the cold neutral medium (CNM) and a dark cloud to estimate the efficiency of coagulation, shattering and segregation of grains.

2. MHD Turbulence and Grain Motion

Unlike hydrodynamic turbulence, MHD turbulence is anisotropic, with eddies elongated along the magnetic field. This happens because it is easier to mix the magnetic field lines perpendicular to their direction rather than to bend them. The energy of eddies drops with the decrease of eddy size (e.g. $v_l \sim l^{1/3}$ for the Kolmogorov turbulence) and it becomes more difficult for smaller eddies to bend the magnetic field lines. Therefore the eddies get more and more anisotropic as their sizes decrease. As eddies mix the magnetic field lines at the rate $k_\perp v_k$, where $k_\perp$is a wavenumber measured in the direction perpendicular to the local magnetic field and v_k is the mixing velocity at this scale, the magnetic perturbations propagate along the magnetic field lines at the rate $k_\| V_A$,where $k_\|$ is the parallel wavenumber and V_A is the Alfven velocity. The corner stone of the GS95 model is a critical balance between those rates, i.e., $k_\perp v_k \sim k_\| V_A$, which may be also viewed as coupling of eddies and wave-like motions. Mixing motions perpendicular to the magnetic field lines are essentially hydrodynamic (see CLV02) and therefore it is not surprising that the GS95 predicted the Kolmogorov one-dimensional energy spectrum in terms of $k_\perp$, i.e., $E(k_\perp) \sim k_\perp^{-5/3}$(see review by Cho, Lazarian & Yan 2002, henceforth CLY02).

The GS95 model describes incompressible MHD turbulence. Recent research suggests that the scaling is approximately true for the dominant Alfvenic modes in a compressible medium with Mach numbers($M \equiv V/C_s$) of the order of unity (Lithwick & Goldreich 2001,

henceforth LG01, CLY02, Cho & Lazarian 2002, in preparation), which is also consistent with the analysis of observational data (Lazarian & Pogosyan 2000, Stanimirovic & Lazarian 2001, CLY02). In what follows we apply the GS95 scaling to handle the problem of grain motions.

Because of turbulence anisotropy, it is convenient to consider separately grain motions parallel and perpendicular to the magnetic field. The motions perpendicular to the magnetic field are influenced by Alfven modes, while those parallel to the magnetic field are subjected to the magnetosonic modes. The scaling relation for perpendicular motion is $v_k \propto k_\perp^{-1/3}$ (GS95). As the eddy turnover time is $\tau_k \propto (k_\perp v_k)^{-1}$, the velocity may be expressed as $v_k \approx v_{max} \left(\tau_k/\tau_{max}\right)^{1/2}$, where $\tau_{max} = l_{max}/v_{max}$ is the time-scale for the largest eddies, for which we adopt the fiducial values $l_{max} = 10$pc, $v_{max} = 5$km/s.

Grains are charged and coupled with the magnetic field. If the Larmor time $\tau_L = 2\pi m_{gr} c/qB$ is shorter than the gas drag time t_{drag}, grain perpendicular motions are constrained by the magnetic field. In this case, grains have a velocity dispersion determined by the turbulence eddy whose turnover period is $\sim \tau_L$, while grains move with the magnetic field on longer time scales. Since the turbulence velocity grows with the eddy size, the largest velocity difference occurs on the largest scale where grains are still decoupled. Thus, following the approach in Draine (1985), we can estimate the characteristic grain velocity relative to the fluid as the velocity of the eddy with a turnover time equal to τ_L,

$$v_\perp(a) = \frac{v_{max}^{3/2}}{l_{max}^{1/2}} (\rho_{gr})^{1/2} \left(\frac{8\pi^2 c}{3qB}\right)^{1/2} a^{3/2}, \qquad (1)$$

and the relative velocity of grains to each other should be approximately equal to the larger one of the grains' velocities, i.e., the the larger grain's velocity,

$$\begin{aligned} \delta v_\perp(a_1, a_2) &= \frac{v_{max}^{3/2}}{l_{max}^{1/2}} (\rho_{gr})^{1/2} \left(\frac{8\pi^2 c}{3qB}\right)^{1/2} [max(a_1, a_2)]^{3/2} \\ &= 1.4 \times 10^5 cm/s (v_5 a_5)^{3/2} / (q_e l_{10} B_\mu)^{1/2}, \qquad (2) \end{aligned}$$

in which $v_5 = v_{max}/10^5$cm/s, $a_5 = a/10^{-5}$cm, $q_e = q/1$electron, $l_{10} = l_{max}/10$pc, $B_\mu = B/1\mu$G, and the grain density is assumed to be $\rho_{gr} = 2.6$g/cm^{-3} .

Grain motions parallel to the magnetic field are induced by the compressive component of slow mode with $v_\parallel \propto k_\parallel^{-1/2}$ (CLV02, LG01, CLY02). The eddy turnover time is $\tau_k \propto (v_\parallel k_\parallel)^{-1}$, so the parallel velocity can be described as $v_\parallel \approx v_{max}\tau_k/\tau_{max}$[1]. For grain motions parallel to the magnetic field the Larmor precession is unimportant and the gas-grain

[1]We assume that turbulence is driven isotropically at the scale l_{max}.

coupling takes place on the translational drag time t_{drag}. The drag time due to collisions with atoms is essentially the time for collision with the mass of gas equal to the mass of grain, $t^0_{drag} = (a\rho_{gr}/n)(\pi/8\mu kT)^{1/2}$., where μ is the mass of gas species. The ion-grain cross-section due to long-range Coulomb force is larger than the atom-grain cross-section (Draine & Salpeter 1979). Therefore, in the presence of collisions with ions, the effective drag time decreases, $t_{drag} = \alpha t^0_{drag}$, where $\alpha < 1$ is the function of a particular ISM phase. The characteristic velocity of grain motions along the magnetic field is approximately equal to the parallel turbulent velocity of eddies with turnover time equal to t_{drag}

$$v_{\|}(a) = \alpha \frac{v^2_{max}}{l_{max}} \left(\frac{\rho_{gr}}{4n}\right) \left(\frac{2\pi}{\mu kT}\right)^{1/2} a, \tag{3}$$

and the relative velocity of grains for $T_{100} = T/100\mathrm{K}$ is

$$\begin{aligned} \delta v_{\|}(a_1, a_2) &= \alpha \frac{v^2_{max}}{l_{max}} \left(\frac{\rho_{gr}}{4n}\right) (\frac{2\pi}{\mu kT})^{1/2} [max(a_1, a_2)] \\ &= (1.0 \times 10^6 cm/s) \alpha v_5^2 a_5 / (n l_{10} T_{100}^{1/2}), \end{aligned} \tag{4}$$

When $\tau_L > t_{drag}$, grains are no longer tied to the magnetic field. Since at a given scale, the largest velocity dispersion is perpendicular to the magnetic field direction, the velocity gradient over the grain mean free path is maximal in the direction perpendicular to the magnetic field direction. The corresponding scaling is analogous to the hydrodynamic case, which was discussed in Draine (1985): $\delta v(a_1, a_2) = v^{3/2}_{max}/l^{1/2}_{max} t^{1/2}_{drag}$, i.e.,

$$\delta v(a_1, a_2) = \alpha^{\frac{1}{2}} \frac{v^{3/2}_{max}}{l^{1/2}_{max}} \left(\frac{\rho_{gr}}{4n}\right)^{\frac{1}{2}} \left(\frac{2\pi}{\mu kT}\right)^{\frac{1}{4}} [max(a_1, a_2)]^{\frac{1}{2}}. \tag{5}$$

Turbulence is damped due to the viscousity when the cascading rate $v_\perp k_\perp$ equals the damping time t_{damp} (see Cho, Lazarian & Vishniac 2002b). If the mean free path for a neutral particle l_n, in a partially ionized gas with density $n_{tot} = n_n + n_i$, is much less than the size of the eddy in consideration, i.e., $l_n k_\perp \ll 1$, the damping time is $t_{damp} \sim \nu_n^{-1} k_\perp^{-2} \sim (n_{tot}/n_n) (l_n v_n)^{-1} k_\perp^{-2}$, where ν_n is effective viscosity produced by neutrals. In the present paper we consider cold gas with low ionization, therefore the influence of ions on l_n is disregarded. Thus the turbulence cutoff time in neutral medium is

$$\tau_c \simeq \left(\frac{l_n}{v_n}\right) \left(\frac{v_n}{v_{max}}\right)^{\frac{3}{2}} \left(\frac{l_{max}}{l_n}\right)^{\frac{1}{2}} \left(\frac{V_A}{v_{max}}\right)^{\frac{1}{2}} \left(\frac{n_n}{n_{tot}}\right), \tag{6}$$

where v_n and V_A are, respectively, the velocity of a neutral and Alfven velocity. It is easy to see that for τ_c longer than either t_{drag} or τ_L the grain motions get modified. A grain samples only a part of the eddy before gaining the velocity of the ambient gas. In GS95 picture, the shear rate dv/dl increases with the decrease of eddy size. Thus for $\tau_c > max\{t_{drag}, \tau_L\}$, these smallest available eddies are the most important for grain acceleration. Consider first the perpendicular motions. If v_c is the velocity of the critically damped eddy, the distance traveled by the grain is $\triangle l \sim v_c \times min\{t_{drag}, \tau_L\}$. Thus the grain experiences the velocity difference $\triangle l \times dv/dl \sim v_c \times min\{t_{drag}, \tau_L\}/\tau_c$. Due to the critical balance in GS95 model, the shear rate along the magnetic field is $dv/dl = v_c k_\parallel \sim v_c/(V_A \tau_c)$. Therefore, grain experiences a velocity difference V_A/v_c times smaller, i.e., $\sim v_c^2 \times t_{drag}/(V_A \tau_c)$.

3. Discussion

3.1. Shattering and Coagulation

Consider the cold neutral medium (CNM) with temperature $T = 100$K, density $n_{\rm H} = 30{\rm cm}^{-3}$, electron density $n_e = 0.045{\rm cm}^{-3}$, magnetic field $B \sim 1.3 \times 10^{-5}$G (Weingartner & Draine 2001a, hereafter WD01a). To account for the Coulomb drag, we use the results by WD01a and get the modified drag time $t_{drag} = \alpha t^0_{drag}$. Using the electric potentials in Weingartner & Draine (2001b), we get grain charge and τ_L.

For the parameters given above, we find that t_{drag} is larger than τ_c for grains larger than 10^{-6}cm, τ_L is smaller than τ_c even for grains as large as 10^{-5}cm. Here, we only consider grains larger than 10^{-6}cm, which carry most grain mass ($\sim 80\%$) in ISM, so we can still use Eq.(3) to calculate grain parallel velocities and Eq.(1) to get the perpendicular velocity for grain larger than 10^{-5}cm. Nevertheless, the perpendicular velocities of grains smaller than 10^{-5}cm should be estimated as $v'_\perp(a) = v_c \times (\tau_L/\tau_c) = v_{max}(\tau_c/\tau_{max})^{1/2}(\tau_L/\tau_c) = v_\perp(a)(\tau_L/\tau_c)^{1/2}$, where $v_\perp(a)$ is given by Eq.(1). The results are shown in Fig.1.

The critical sticking velocity were calculated in Chokshi et al. (1993)(see also Dominik & Tielens 1997).[2] However, experimental work by Blum (2000) shows that the critical velocity is an order of magnitude larger than the theoretical calculation. Thus the collisions can result in coagulation for small silicate grains ($\leq 3 \times 10^{-6}$cm).

With our input parameters, grains do not shatter if the shattering thresholds for silicate

[2]There are obvious misprints in the numerical coefficient of Eq.(7) in Chokshi et al.(1993) and the power index of Young's modulus in Eq.(28) of Dominik & Tielens (1997).

is 2.7km/s as in Jones et al. (1996). Nevertheless, the grain velocities strongly depend on v_{max} at the injection scale. For instance, we will get a cutoff 6×10^{-5}cm due to shattering if $v_{max} = 10$km/s.

For a dark cloud, the situation is different. As the density increases, the drag by gas becomes stronger. Consider a typical dark cloud with temperature $T = 20$K, density $n_{\rm H} = 10^4$cm^{-3} (Chokshi et al. 1993) and magnetic field $B \sim 2.3 \times 10^{-4}$G. Assuming that dark clouds are shielded from radiation, grains get charged by collisions with electrons: $< q >= 0.3(r/10^{-5}{\rm cm})$ electrons. The ionization in the cloud is $\chi = n_e/n_{tot} \sim 10^{-6}$ and the drag by neutral atoms is dominant. From Eq.(6) and the expression for the drag time and the Larmor time, we find $\tau_L < t_{drag}$ for grains of sizes between 10^{-6}cm and 4×10^{-6}cm, and $t_{drag} < \tau_L$ for grains larger than 4×10^{-6}cm. In both cases, turbulence cutoff τ_c is smaller than t_{drag} and τ_L. Thus for the smaller grains, we use Eq.(1),(3) to estimate grain velocities. For larger grains, grain velocities are given by Eq.(5).

Our results for dark clouds show only a slight difference from the earlier hydrodynamic estimates. Since the drag time $t_{drag} \propto n^{-1}$, Larmor time $\tau_L \propto B^{-1} \propto n^{-1/2}$, the grain motions get less affected by the magnetic field as the cloud becomes denser. Thus we agree with Chokshi's et al. (1993) conclusion that densities well in excess of 10^4cm^{-3} are required for coagulation to occur. Shattering will not happen because the velocities are small, so there are more large grains in dark clouds. This agrees with observations (see Mathis 1990).

In the treatment above we disregarded the possibility of direct acceleration of charged grains through their interactions with fluctuating magnetic field. In our next paper we will show that this resonant process is important for a highly ionized medium.

3.2. Grain Segregation and Turbulent Mixing

Our results are also relevant to grain segregation. Grains are the major carrier of heavy elements in the ISM. The issue of grain segregation may have significant influence on the ISM metallicity. Subjected to external forcing, e.g., due to radiation pressure, grains gain size-dependent velocities with respect to gas. WD01a have considered the forces on dust grains exposed to anisotropic interstellar radiation fields. They included photoelectric emission, photodesorption as well as radiation pressure, and calculated the drift velocity for grains of different sizes. The velocities they got for silicate grains in the CNM range from 0.1cm/s to

10^3cm/s. Fig.1 shows that the turbulence produces larger velocity dispersions.[3] Thus the grain segregation of very small and large grains speculated in de Oliveira-Costa et al. (2000) is unlikely to happen for typical CNM conditions.

A different mechanism of driving grain motions is a residual imbalance in "rocket thrust" between the opposite surfaces of a rotating grain (Purcell 1979). This mechanism can provide grain relative motions and preferentially move grains into molecular clouds. It is easy to see that due to averaging caused by grain rotation, the rocket thrust is parallel to the rotation axis. Three causes for the thrust were suggested by Purcell (1979): spatial variation of the accommodation coefficient for impinging atoms, photoelectric emission, and H_2 formation. The latter was shown to be the strongest among the three. The uncompensated force in this case arises from the difference of the number of catalytic active sites for H_2 formation on the opposite grain surfaces. The nascent H_2 molecules leave the active sites with kinetic energy E and the grain experiences a push in the opposite directions. The number of active sites varies from one grain to another, and we should deal with the expectation value of the force for a given distribution of active sites.

Due to internal relaxation of energy (see Lazarian & Draine 1999a,b, and review by Lazarian 2000) the grain rotational axis tends to be perpendicular to the largest $b-b$ surface. Adopting the approach in Lazarian & Draine (1997), we get the mean square root force of H_2 thrust on a grain in the shape of a square prism with dimensions $b\times b\times a$ $(b>a)$

$$\langle F_{z\mathrm{H}}\rangle = r^{3/2}(r+1)^{1/2}\gamma(1-y)n_{\mathrm{H}}v_{\mathrm{H}}a^2\left(\frac{2m_{\mathrm{H}}E}{\nu}\right)^{1/2}, \tag{7}$$

where $r=b/2a$,, $n_{\mathrm{H}}\equiv n(\mathrm{H})+2n(\mathrm{H}_2)$, $y=2n(\mathrm{H}_2)/n_{\mathrm{H}}$ is the H_2 fraction, γ is the fraction of impinging H atoms and ν is the number of active sites over the grain surface. The expected grain velocity is $v=\langle F_{z\mathrm{H}}\rangle t_{drag}/m$. In the CNM we consider, $y=0$, adopting the characteristic values in Lazarian & Draine (1997), $r=1$, $\gamma=0.2$, $E=0.2$eV, and the density of active sites $10^{11}\mathrm{cm}^{-2}$ so that $\nu=80(a/10^{-5}\mathrm{cm})^2r(r+1)$, we get the "optimistic" velocity shown in Fig 1. For maximal active site density $10^{15}\mathrm{cm}^{-2}$, we get the lower boundary of grain velocity $v\simeq 3.3(10^{-5}\mathrm{cm}/a)^{1/2}$cm/s. The scaling is approximate due to the complexity of coefficient α(see WD01a Fig.16).

Lazarian & Draine (1999a,b) have shown that subjected to H_2 torques alone, grains $\leq 10^{-4}$cm should experience frequent thermal flipping, which means that the $F_{z\mathrm{H}}$ fluctuates. This flipping results from coupling of grain rotational and vibrational degrees of freedom

[3]If reconnection is fast (see Lazarian & Vishniac 1999), the mixing of grains over large scales is provided by turbulent diffusivity$\sim v_{max}l_{max}$. On small scales the grain decoupled motions are important.

through internal relaxation and would average out $\langle F_{z\mathrm{H}} \rangle$. However, the flipping rate depends on the value of the grain angular momentum (Lazarian & Draine 1999a). If a grain is already spun up to a sufficient velocity, it gets immune to thermal flipping. Radiative torques (Draine & Weingartner 1996) can provide efficient spin if the grain size is comparable to the wavelength. For a typical interstellar diffuse radiation field, the radiative torques are expected to spin up grains with sizes larger than $\sim 4 \times 10^{-6}$cm. They will also align grains with rotational axes parallel to the magnetic field. Thus grains should acquire velocities along the magnetic field lines and the corresponding velocities should be compared with those arising from turbulent motions parallel to the magnetic field. It is clear from Fig.1 that for the chosen set of parameters the effect of H_2 thrust is limited. All in all, we conclude that the radiation effects and H_2 thrust are not efficient for segregating grains in typical ISM conditions.

4. Summary

We have calculated relative motions of dust grains in a magnetized turbulent fluid taking into account turbulence anisotropy, turbulence damping and grain coupling with the magnetic field. We find that these effects decrease the relative velocities of dust grains compared to the earlier hydrodynamic-based calculations. The difference is substantial in CNM, but less important for dark clouds. For CNM we find that coagulations of silicate grains happen for sizes $\leq 3 \times 10^{-6}$cm. The force due to H_2 formation on grain surface might drive small grains ($< 3 \times 10^{-6}$cm) to larger velocities but thermal flipping of grains suppresses the forces for grains less than 4×10^{-6}cm. We conclude that radiation and H_2 thrust are not capable of segregating grains.

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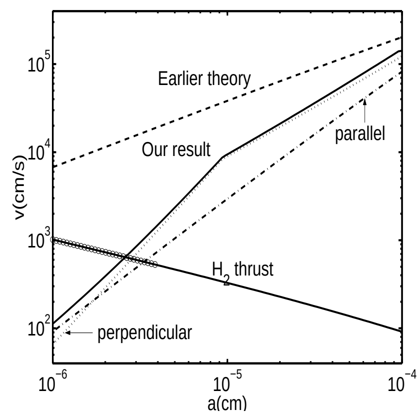

Fig. 1.— Grain velocities as a function of radii (solid line) in the CNM. Dashdot line represents parallel velocity due to the drag by compressible modes, dotted line refers to perpendicular velocity from the contribution of the drag by Alfven mode, also plotted is the earlier hydrodynamic result (dashed line). The change of the slope is due to the cutoff of turbulence by ambipolar diffusion. The grain velocity driven by H_2 thrust is plotted to illustrate the issue of grain segregation in the CNM (see text), the part marked by 'o' is nonphysical because thermal flipping is not taken into account.